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# Science with the Space Interferometry Mission


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**April 21, 2000**

# Summary

- What is SIM ?
  - Scientific drivers and performance
  - Brief summary of instrument
- How SIM performs astrometry
- How SIM does imaging
- SIM science program
  - Astrometric detection of extrasolar planets
  - Galactic dynamics
  - Rotational parallaxes of galaxies
  - Using gravitational lenses to probe dark matter
  - Stellar astrophysics
- SIM project status

# What is SIM ?

- SIM is a space-based optical interferometer for precision astrometry
  - 10-m baseline, Michelson beam combiner
- Launch mid-2006, with a minimum 5-year mission lifetime
- SIM has 4 basic operating modes
  - Global astrometry
  - Local astrometry
  - Synthesis imaging
  - Fringe nulling demonstration for future missions
- How does it operate ?
  - SIM measures the white-light fringe position on 3 simultaneous baselines: 2 guides and 1 science
  - Using delay and angle feed-forward, the guides stabilize the science interferometer at the microarcsecond level
- For more information visit the SIM web site:
  - **`http://sim.jpl.nasa.gov/`**

# What is SIM ?

Technology maturation
over the next few years
will determine the ultimate
achievable
performance

## Technology

Demonstrate Technology
of Synthesis Imaging

Demonstrate Technology
of Starlight Nulling

Usher in the Era of

Long Baseline, Short Wavelength
Interferometry for
Astrophysical Observation

## Science

Indirect Planet Detection
Down to a Few Earth Masses
goal: 1 μas

Ultra Precision
Global Astrometry
goal: 4 μas

Artist’s impression of the SIM spacecraft, operating in a solar Earth-trailing orbit

# Development of the SIM science program

- Bahcall Report (National Academy of Sciences, 1991) "The Decade of Discovery"
  - Recommended an astrometric mission with an accuracy of 3 - 30 microarcseconds (μas)
    - Search for planets around stars within 150 pc
    - Distances to stars throughout the Galaxy
    - Demonstrate technology for future interferometry missions

- SIM Science Working Group
  - Team of ~20 scientists with astronomy / technology interests
  - Develop Science Requirements and advise NASA
  - Final Report (February 2000)
    - now available in hardcopy or on SIM web site

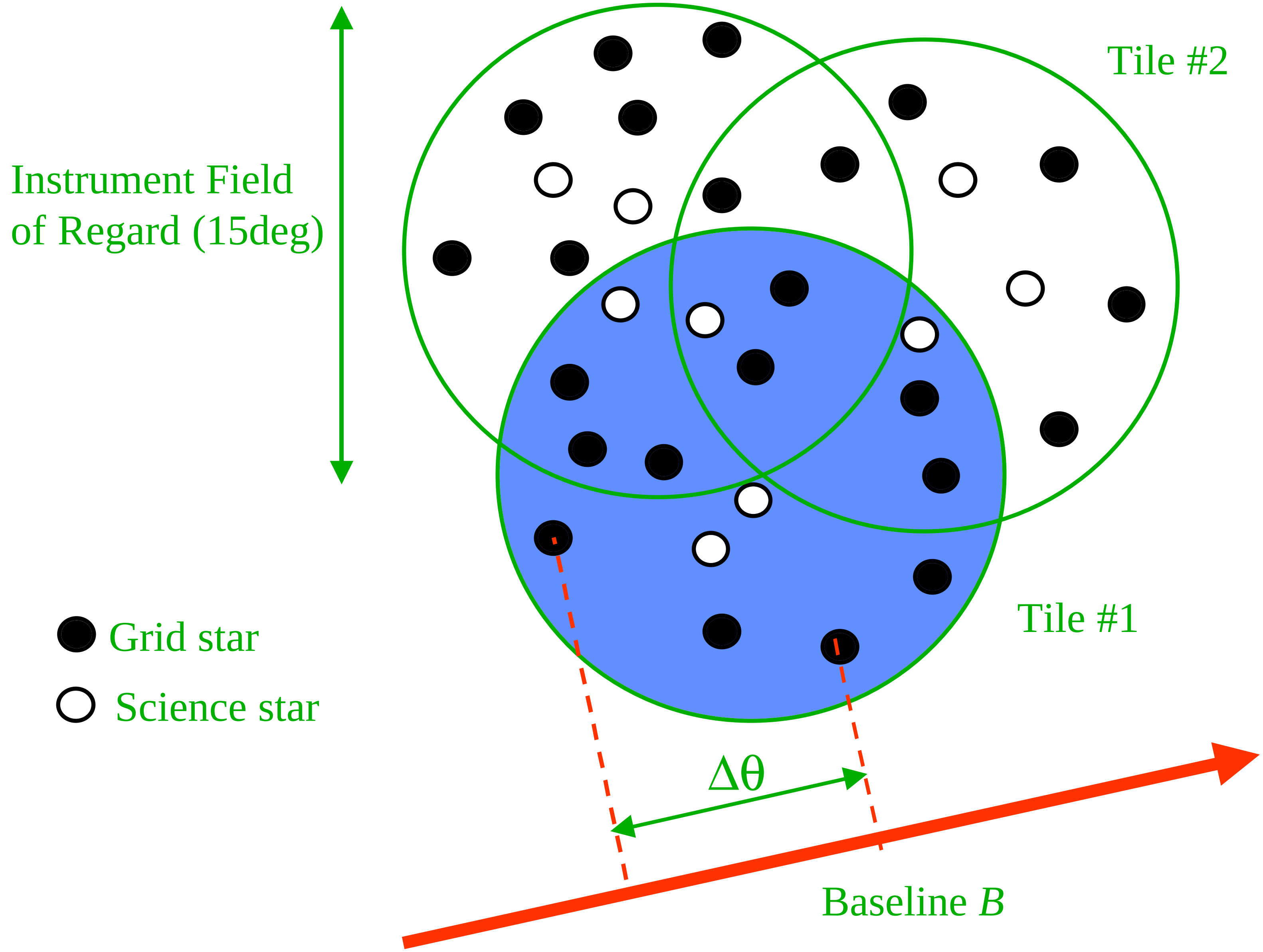
- SIM Science Team
  - AO for Science Team released - February 2000
  - Proposals due - May 2000
  - Team selection - September 2000

# SIM astrometric performance summary

- **Global (all-sky) astrometry**
  - Astrometric accuracy: 4 μas (end of mission)
  - Faintest stars: V = 20 mag (solar-type star at 10 kpc)
  - Yields distances to 10% accuracy, anywhere in our Galaxy

- **Local (narrow-angle) astrometry**
  - Measurements are made relative to reference stars (within ~1° field)
  - Astrometric accuracy: 1 μas in one hour
    - This angle subtends a length of 1,500 km at 10 pc distance
      - *From Pasadena to Denver, at a distance of 30 light years*
    - Proper motion accuracy: 2 μas / yr
      - Motion due to parallax at 10 pc is detectable in a few minutes!
      - *Speed of a fast car at center of our Galaxy: 25000 light years*

# Grid Observing Scenario

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# SIM science summary

- Planet searching:
  - Search for astrometric signature of terrestrial planets around nearby stars
  - Statistics and properties of planetary systems
- Distances and Luminosities:
  - Spiral galaxy distances using rotational parallaxes
  - Calibration of the cosmic distance ‘ladder’
  - Ages of globular clusters
- Galaxy and star cluster dynamics and structure
  - Mass distribution in the halo of our Galaxy
  - Spiral structure of our Galaxy
  - Internal dynamics of globular clusters
  - Masses and distances to gravitational lenses
  - Dynamics of our Local Group of galaxies
- Imaging:
  - Emission-line gas around black holes in active galactic nuclei
  - Dust disks around nearby stars (nulling)

# Measuring Distances in the Galaxy

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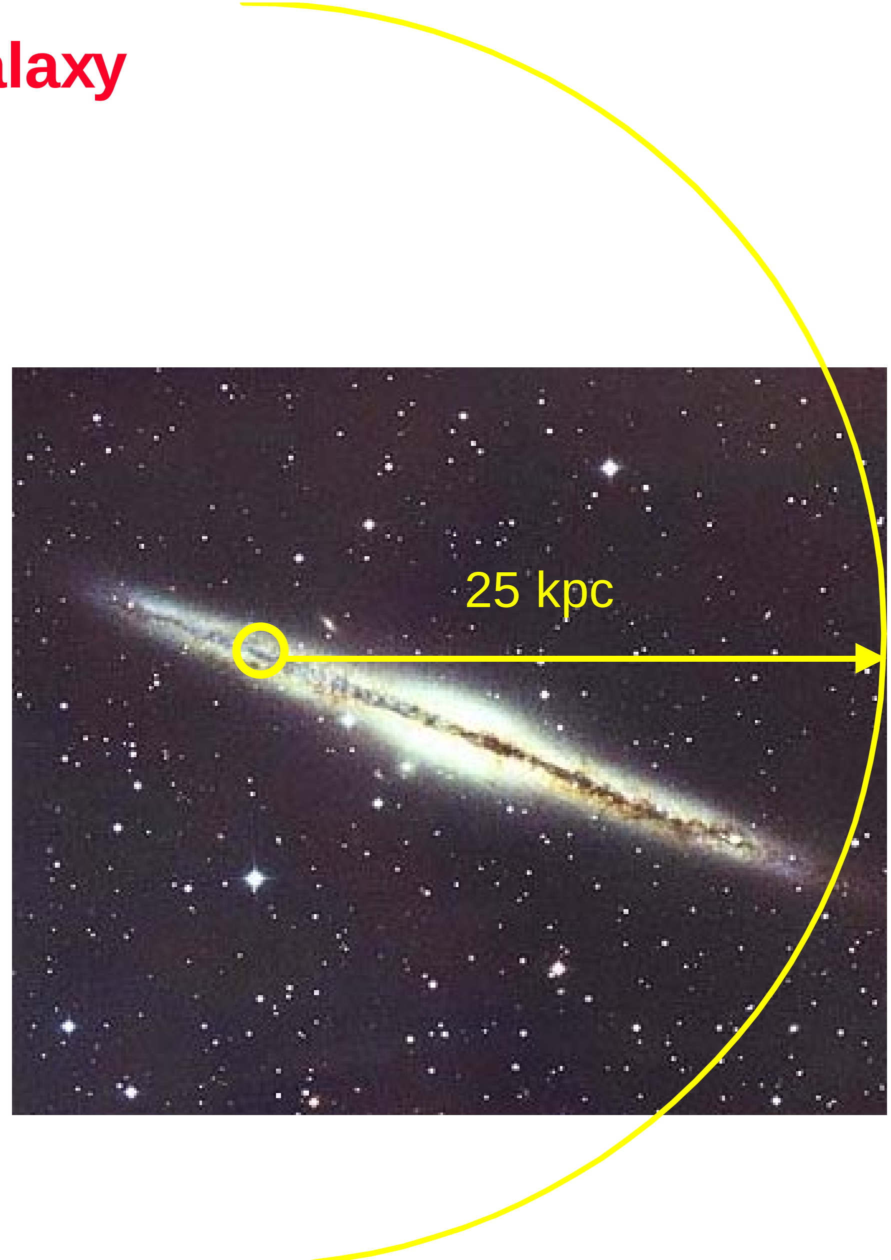
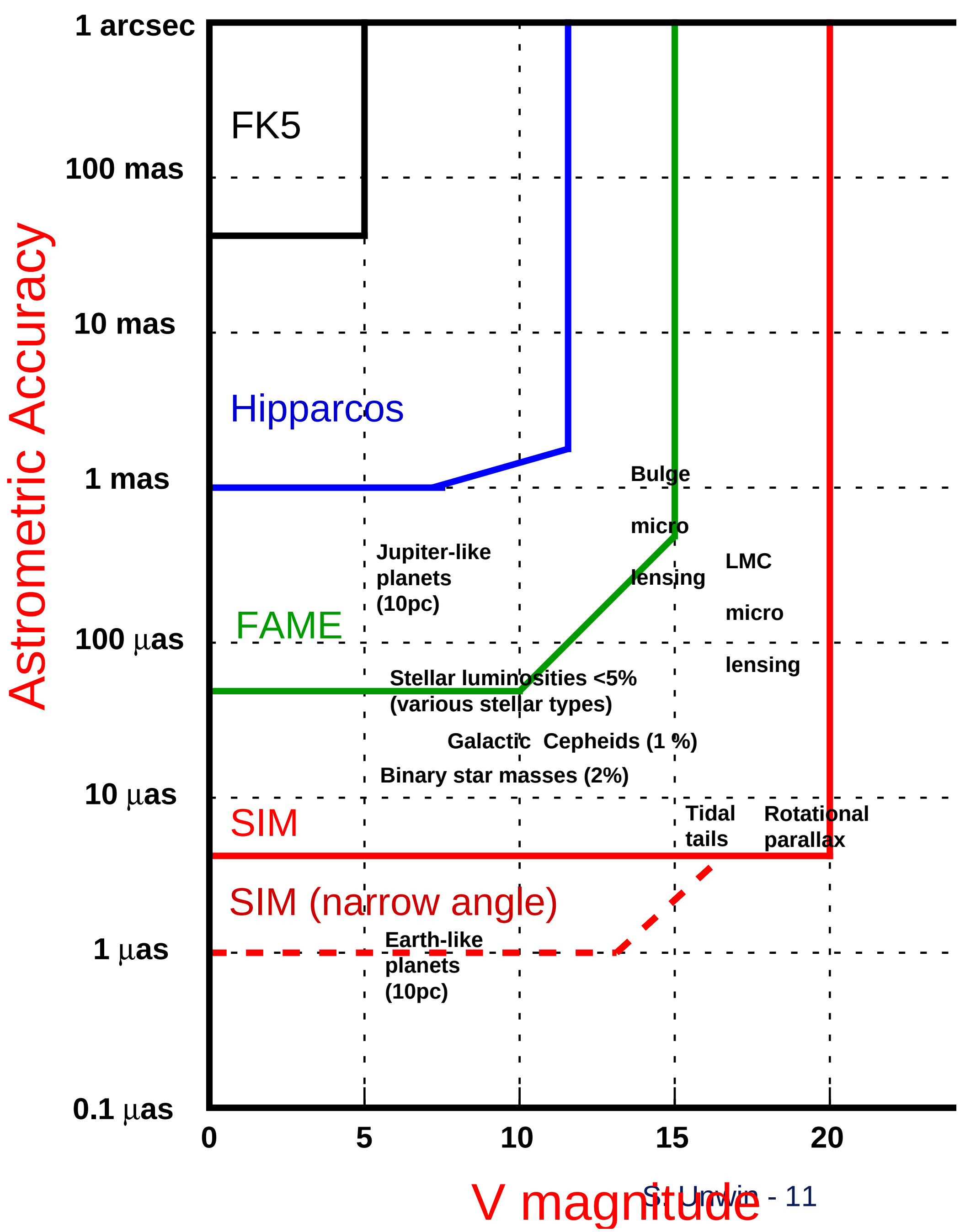
- SIM will reach high accuracy on faint targets
  - 4 µas positions
  - 3 µas / yr proper motions
  - Limiting mag V = 20
- G-dwarf at 3 kpc:
  - V = 17.5, accuracy 1 %
- KIII giant at 25 kpc:
  - V = 15, accuracy 10 %
- Combination enables demanding programs, like:
  - rotational parallaxes
  - tidal tails of disrupted dwarf galaxies



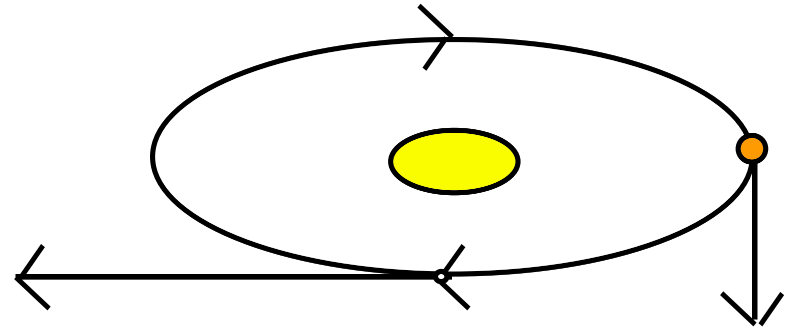
# Astrometric Parameter Space

- SIM will reach
  - V = 20 and 4 µas accuracy (global)
  - 1  µas accuracy (local)
- Enables demanding programs such as:
  - Terrestrial planets
  - Rotational parallaxes
  - ‘Tidal tails’ of disrupted dwarf galaxies

# Global Astrometric Accuracy



# Measuring distances to spiral galaxies using rotational parallaxes

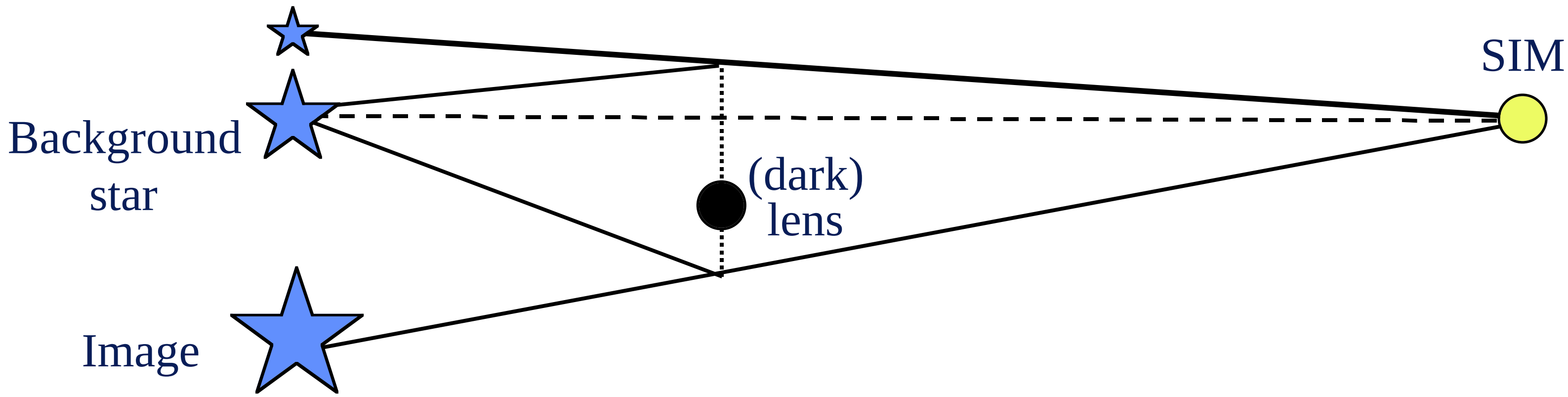


Transverse velocity = $V_{rot} = \mu_{rot}$ D

Radial velocity = $V_{rot}$ sin i
Transverse velocity = $V_{rot}$ cos i

- What ? **Measure distance to a galaxy in units of meters - in a 'single step'**
  - Other methods involve a 'distance ladder' of several steps
  - Applicable to the nearest spiral galaxies - out to a few Mpc, to a few %
- How ? **Directly measure rotation of stars in galactic disk**
  - SIM measures transverse proper motion: $\mu_{rot}$
  - Measure radial velocities by ground-based spectroscopy: $V_{rot}$ sin i
  - *Ratio* gives the distance directly
- Why ? **Scientific importance**
  - *Independent* calibration of a population of Cepheids in an external galaxy
    - Cepheid stars are the single most important 'standard candle'
  - Spiral galaxies are *themselves* used as 'standard candles' for more distant objects in the Universe
    - SIM will calibrate these 'candles'

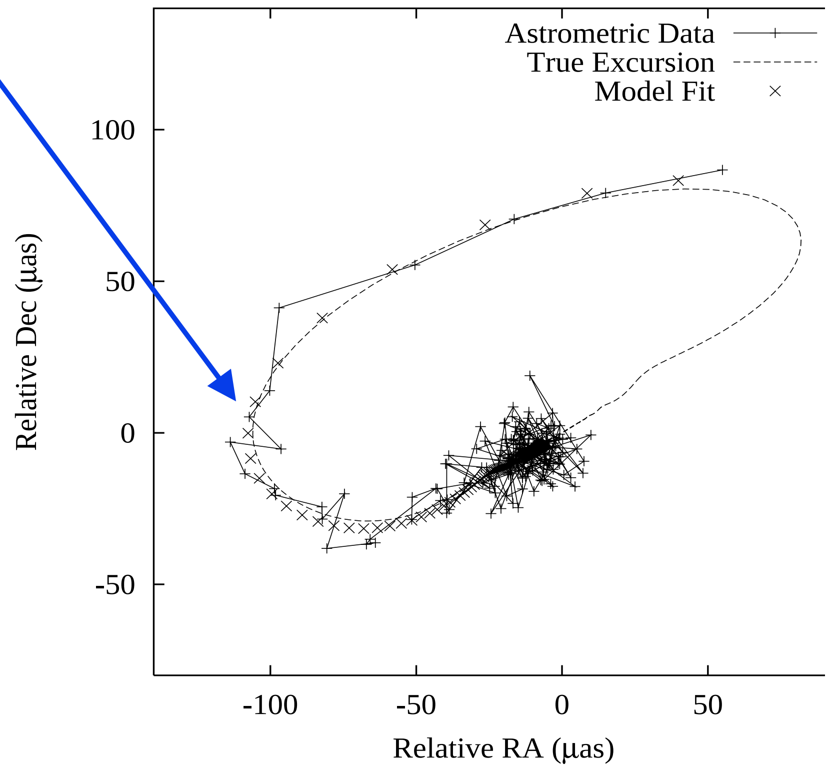
# Using Gravitational Lenses to Probe 'Dark Matter'




- Microlensing is the gravitational bending of light by chance alignments of stars
- Events are detected by
  - Brightness enhancement (~days)
  - Astrometric perturbation (~weeks to months)
- Interpretation of current LMC lensing results is ambiguous
  - SIM would enable measurement of lens distances (in LMC or in our Galaxy?)
- Observing program:
  - Ground-based *photometric* monitoring program of many stars in the Large Magellanic Cloud (LMC)
  - SIM performs *astrometry* on detected events as 'targets of opportunity'

# Using Gravitational Lenses to Probe 'Dark Matter' (cont.)

- Apparent star position moves in a characteristic pattern with relatively large amplitude of ~100 µas
- Symmetry of track 'broken' by Earth orbit motion
  - due to lens parallax
  - Hence: distance to lens
- Derive: mass, distance, and velocity of the lensing object

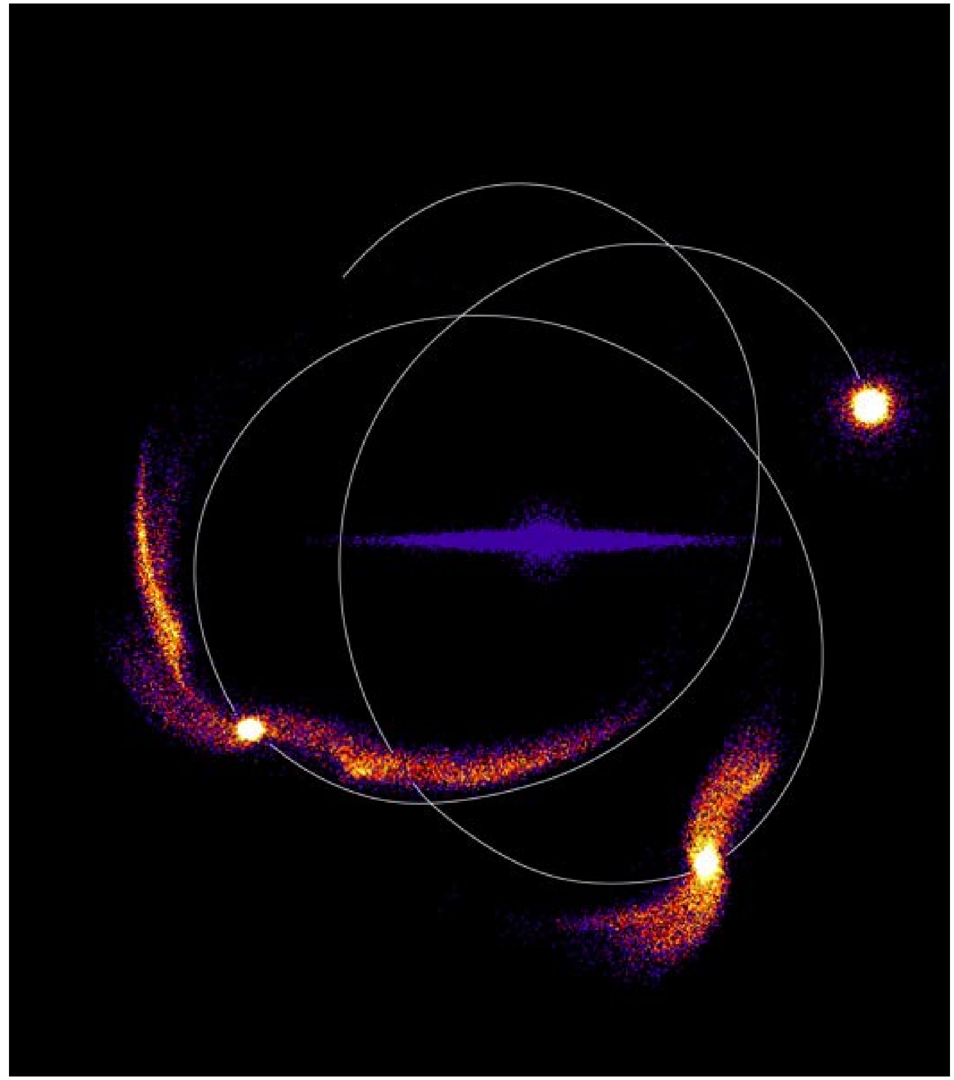


# Galactic Dynamics



- Study the 'classical' problems of size, mass distribution, and dynamics of the Galaxy, using stellar velocities

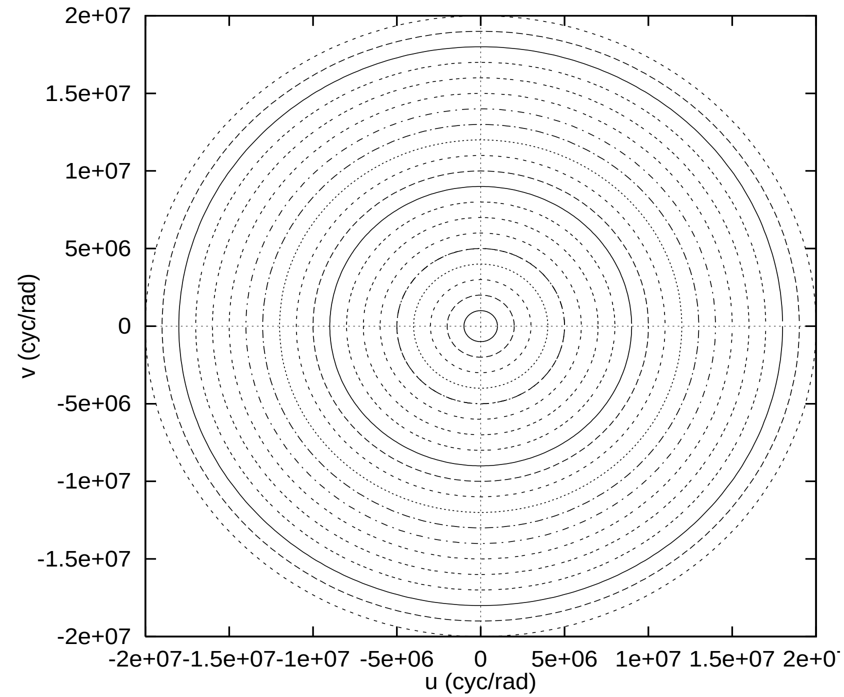
- Example:
  – Debris tail orbits (Sagittarius dwarf galaxy)
    - characteristic phase space signature
  – Distances to 5% at 10 kpc, for stars with V < 20
  – Proper motions to 0.1 km/s at 10 kpc
  – Combine with ground-based radial velocities

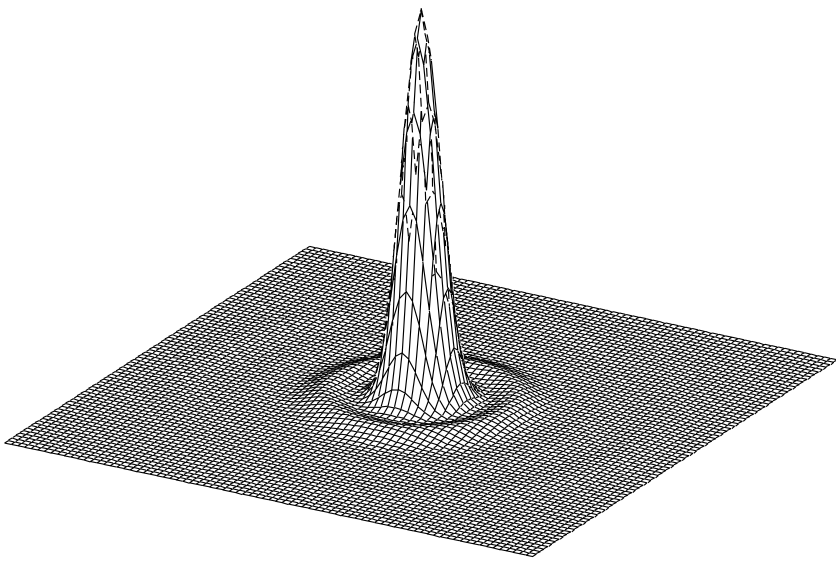


**'Tidal tail' simulation:**
**Dwarf galaxy in orbit around the Milky Way**

# Imaging with SIM

- SIM forms images by *synthesizing* the equivalent of a 10-meter aperture
  - Fully diffraction-limited
  - Operation down to 4000 Angstroms
  - Fully phase-stable:
    - High dynamic range

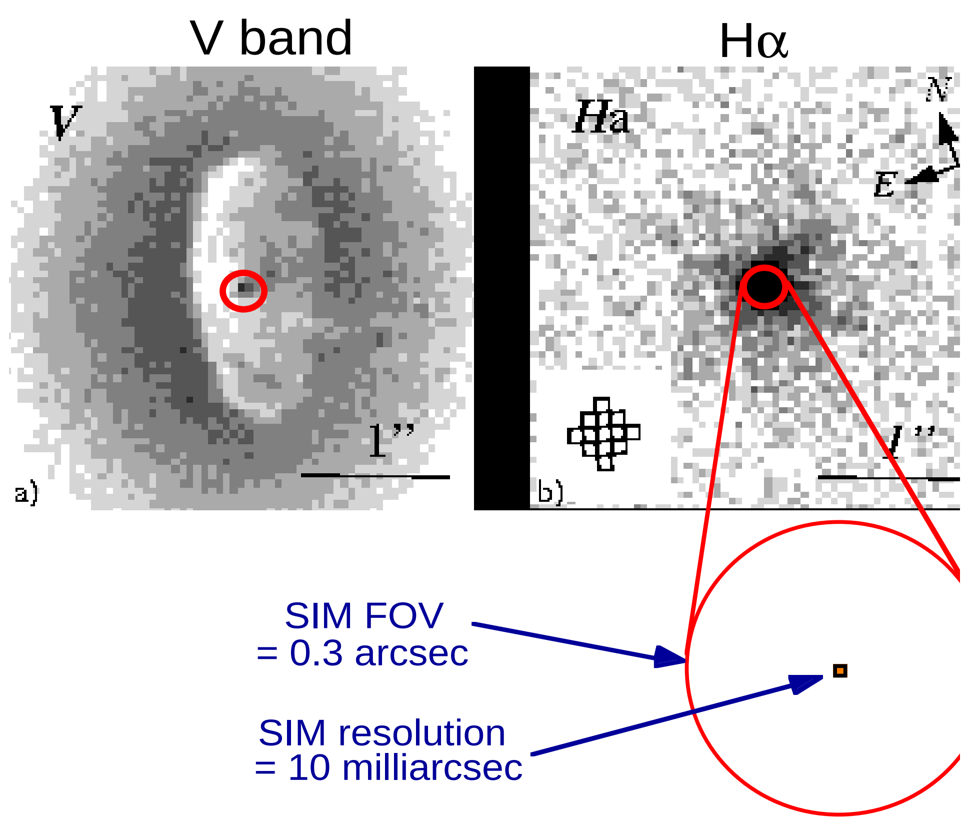


# Massive black holes in active galactic nuclei
# Example:  NGC 4261

- HST / WFPC2 images show an dust disk surrounding a bright emission-line region centered on the nucleus
- HST spectra indicate nucleus contains a massive black hole
- SIM can image the central 0.3 arcsec at 10 milliarcsecond resolution
- Detect and measure black hole mass using Doppler-shift of the Hα line

**HST/WFPC2 images of nucleus of NGC4261, at a distance of 30 Mpc (Ferrarese et al. 1996)**



# Planetary Systems: Questions

- Statistics of planetary systems
  - How common are planetary systems?
  - Are certain star types favored?
  - What is the distribution of planetary systems in the Galaxy?

- Characterizing planetary systems
  - What are the orbit radii?
  - Are the orbits circular or eccentric?
  - Are multiple-planet systems common?

- For multiple planet systems
  - What is the *typical* mass distribution of planets in a system?
  - What is the *typical* radius distribution?
  - Are the orbits co-planar?
    - *Must* have astrometry to answer this
  - Are the planets stable?

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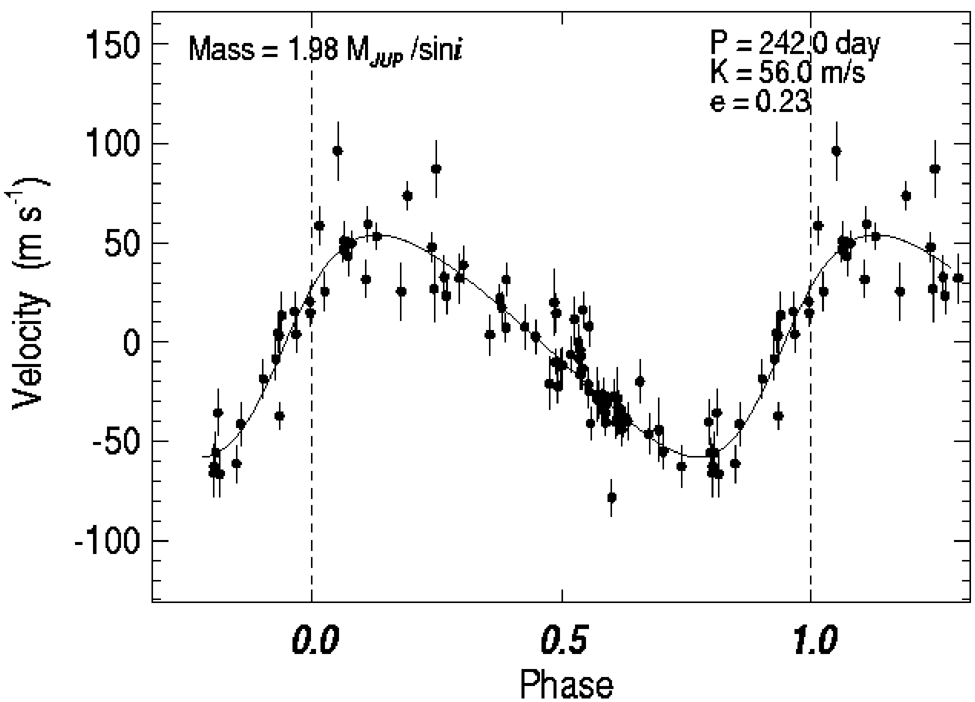
# Properties of Upsilon Andromedae System

- Stellar type F8V, 1.3 solar mass
- Distance = 15 pc
- Planetary companions:
  - b: mass 0.72 $M_{jup}$ orbit radius 0.06 AU period 4.6 days
  - c: mass 1.98 $M_{jup}$ orbit radius 0.83 AU period 242 days
  - d: mass 4.11 $M_{jup}$ orbit radius 2.50 AU period 1269 days
- Ref: Butler, *et al.* 1999, *ApJ* (submitted)

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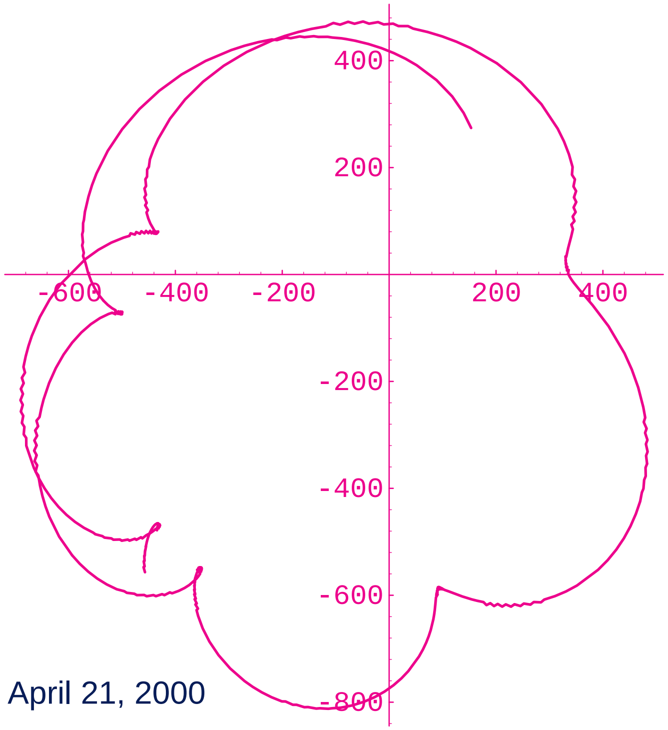
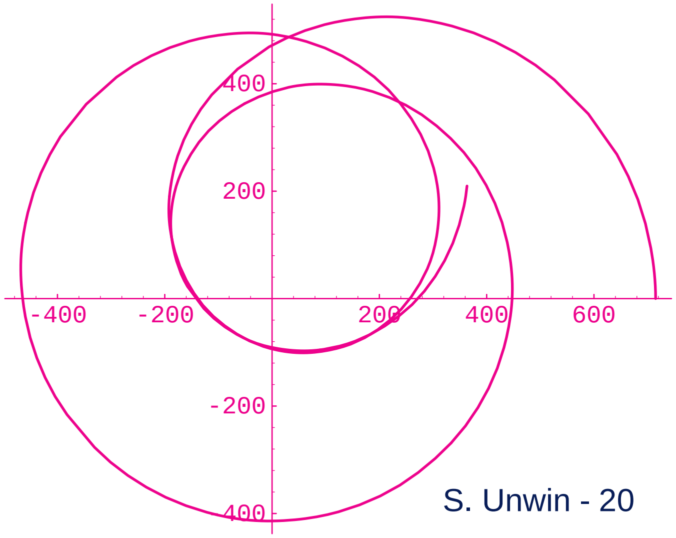
# Astrometric Detection of Upsilon Andromedae

- Astrometric signature:
  - b: amplitude = 2.3 µas radial velocity 70 m/s
  - c: amplitude = 89.3 µas radial velocity 58 m/s
  - d: amplitude = 557.5 µas radial velocity 70 m/s
- Distance: 15 pc

**Upsilon Andromedae**
viewed face on




**Our Solar system**
viewed from 15 pc, face-on

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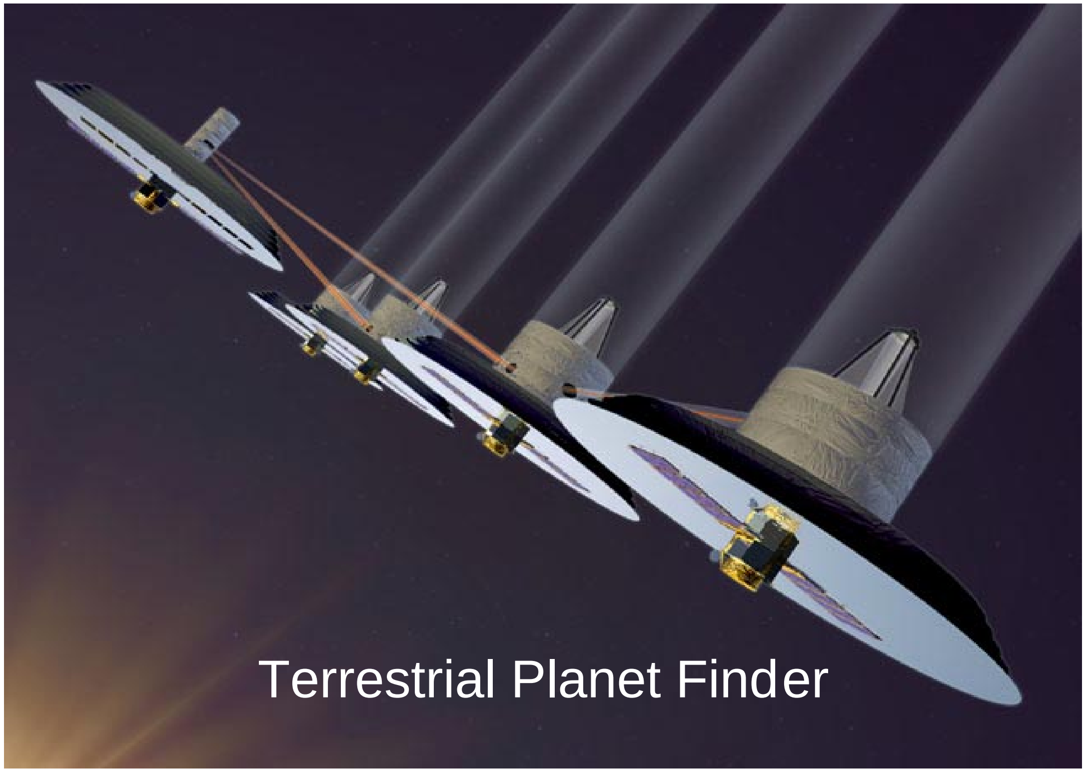
# Toward Future Missions




- SIM will serve as a technology precursor for future interferometers in space
- A direct precursor to the Terrestrial Planet Finder
- Demonstrate:
  - Operation of a Michelson interferometer in space
  - Fringe nulling
  - Control of thermal and vibration environment
  - Synthesis imaging in space
  - Precision deployments
  - Angle and pathlength control

# Conclusions

- SIM is a space-based optical interferometer for precision astrometry
  - 10-m baseline, Michelson beam combiner
- Launch mid-2006, with a 5-year mission lifetime
- SIM has a broad science program
  - Astrometric detection of extrasolar planets
    - Detect planets with a range of masses down to a few Earth masses
  - Galactic dynamics
  - Rotational parallaxes of galaxies
  - Using gravitational lenses to probe dark matter
  - Stellar astrophysics
  - etc…....
- SIM will serve as a technology precursor for future interferometers in space